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ORIENTATION OF CARBONATE LAMINATIONS IN GRAVELLY SOILS ALONG A WINTER/SUMMER PRECIPITATION GRADIENT IN BAJA CALIFORNIA, MEXICO

Amundson, Ronald[1]; Graham, R. C.[2]; Franco-Vizcaíno, Ernesto[3]

Author Information

[1]Div. of Ecosystem Sci., 151 Hilgard Hall, Univ. of Calif., Berkeley, CA 94720. Dr. Amundson is corresponding author. E-mail: (earthy@nature.berkeley.edu).

[2]R.C. Graham, Dept. of Soils and Environ. Sci., Univ. of Calif., Riverside, CA 92521-0424.

[3]E. Franco-Vizcaíno, Departamento de Ecología, Centro de Investigación Superior de Ensenada (CICESE), Ensenada, Baja California, 22800 Mexico; and Department of Earth Systems Science & Policy, California State University, Montery Bay, Seaside, CA 93955-8001.

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Outline

Abstract

We observed, along a north-to-south transect in central Baja California, that the positioning(top vs. bottom) of pedogenic carbonate on gravel in Holocene soils was related to the proportion of winter versus summer/early fall precipitation.

Carbonate coatings were found on gravel bottoms at sites where precipitation occurs predominantly in winter but on gravel tops at sites where summer/fall precipitation is dominant. The positioning of carbonate coatings co-varied with other ecosystem properties such as floral distribution, oxygen isotope composition of carbonate, and depth to the top of the Bk horizon in response to precipitation patterns. The processes responsible for the orientation of carbonate on gravels are unknown. We proposed that the nature of soil thermal gradients during major precipitation events or periods may influence carbonate solubility and, therefore, the loci of deposition. While the deposition of carbonate on gravel tops is apparently unique and restricted to areas of summer/fall precipitation in Baja California, the positioning of carbonate coatings in gravelly soils in this region may also provide some insight into long-term climate patterns in the perarid regions of the Sonoran Desert.

The occurrence of pedogenic carbonate is one of the most common and recognizable features of many desert soils. Observations of the process of pedogenic carbonate accumulation in desert soils are well documented (Gile et al. 1996; Machette 1985), and the process is known to follow predictable pathways, depending on the nature of the parent material (fine-grained vs. gravelly). In gravelly soils, such as those studied here, substantial amounts of pore space surrounding the gravels in young fluvial deposits are commonly-found. As pedogenesis proceeds, dissolved carbonate in the soil solution (derived from calcareous dust, limestone alluvium, or weathering of Ca-bearing silicates) is deposited on gravels as the water is depleted via evapotranspiration. The depth of deposition is related to the balance of precipitation to evapotranspiration and the soil's water-holding capacity (Arkley 1963; McFadden and Tinsley 1985; Marion et al. 1985). Deposition is reported to occur on the gravel bottoms (Gile et al. 1966), although in several of the research areas reported here, deposition occurs primarily on gravel tops.

Up to six stages of gravel coatings and pore infillings have been described (Machette 1985), the terminal stages of which involve thick laminations on clasts, pore infilling, and volumetric expansion of the soil.

In the early stages of development (stages I and II) at areas described here and elsewhere (Chadwick et al. 1989; Amundson et al. 1994b), the carbonate appears to accumulate in unrestricted pore space, developing distinct, nearly horizontal laminae. The innermost laminations are dense, nearly pure pedogenic carbonate, with minor inclusions of detrital silicates and (where present) carbonate. In contrast, the outermost layers, where deposition is actively occurring, can consist of a heterogeneous mixture of pedogenic carbonate and detrital grains (Chadwick et al. 1989; Amundson et al. 1989). The deposition of the dense laminations appears to exclude nonpedogenic minerals (particularly silicates). Even in limestone terrain, the inclusion of detrital limestone in the pedogenic laminations is a minor or undetectable component as shown by stable isotope ([delta]^{13}C, [delta]^{18}O) and radiocarbon studies on side-by-side limestone and nonlimestone soils of identical ages and climates (Quade et al. 1989; Amundson et al. 1989; Wang et al. 1996).

During a reconnaissance study of the effect of precipitation seasonality on the flora and isotope chemistry of pedogenic carbonate in Baja California, Mexico (Amundson et al. 1994a), we encountered a systematic variation in the positioning of carbonate coatings on soil gravels that correlates with the seasonality of precipitation. In this paper we present our observations and evaluate a conceptual model that may explain the processes forming these observed features.

Back to Top

MATERIALS AND METHODS

A detailed description of the climatic and biotic conditions of the study sites is presented elsewhere (Amundson et al. 1994a). Briefly, four study sites were selected on stable Holocene stream terraces along the central axis of the peninsula of Baja California, Mexico (Fig. 1). The geomorphology of the stream margins was similar to that described by McAuliffe (1991). Three distinct Holocene geomorphic surfaces were observed: (i) an active stream wash, (ii) a gravelly, partially vegetated bar deposit, and (iii) a stable terrace, elevated 1 to 2 m above the active wash (Fig. 2). The terrace consisted of approximately 50 cm of gravel-poor alluvium over a more gravel-rich alluvium and showed no evidence of recent flooding or stream modification(organic C distribution decreased regularly with depth) (Amundson et al. 1994a), verifying the relatively long-term stability of these landforms. Pleistocene stream terraces (based on relative landscape position and degree of soil development), which were not studied in any detail in this study, were present at higher elevations adjacent to the Holocene landforms.

Study sites were chosen so that the two northern sites fell within the region of predominantly winter precipitation ("winter precipitation") and the two southern sites fell within the region with a distinctive late summer/early fall precipitation ("summer precipitation"). The climatic conditions of the study sites are given in Table 1. The two northernmost sites receive nearly 50% of their MAP in the first 3 calendar months of each year, primarily from winter Pacific cyclonic storms (Hastings and Turner 1965). The two southernmost sites receive most of their precipitation in the late summer or early fall months, primarily from Pacific tropical cyclones or the North American monsoon (Hastings and Turner 1965).

Additional soil profile observations were made from road and stream cuts in the eastern Baja California peninsula, west and south of San Felipe, at approximately 31°N. This area, which lies

east of the Sierra San Pedro Mártir, is subject to summer storms that are unable to cross the high Sierra and affect areas to the west (i.e., the winter rainfall portion of our transect described above). Thunderstorms associated with the North American monsoon develop over the Sierra San Pedro Mártir in summer, and rain falls on the desert to the east as storm cells drift away from the mountain (Minnich et al. 1993; Minnich et al., manuscript in review). In addition, this area also receives a high proportion of its rainfall from tropical cyclones (Minnich et al. manuscript in review), similar to the two southern"summer" sites described above.

Sites were chosen for morphological and chemical study on representative examples of stable Holocene stream terraces (Amundson et al. 1994a). Soil profiles were exposed through hand excavation. Morphological descriptions were made in the field using standard procedures (Soil Survey Staff 1981). Additional soil profile observations were made from road and stream cuts on alluvial deposits east of the Sierra San Pedro Mártir.

Back to Top

RESULTS AND DISCUSSION

Soil profile descriptions for the northern-and southernmost study sites are given in Table 2. In all soils, carbonate accumulated visibly predominantly on gravels. In the southernmost soil, the fine grained matrix appeared carbonate-free (based on field tests), and all pedogenic carbonate appeared to accumulate on gravels. It was observed that the location of carbonate deposition was (i) entirely on the gravel bottoms in the two northernmost sites and (ii) almost entirely on gravel tops in the two southernmost sites. In addition to the placement of laminations on gravels, there was a pronounced difference in the depth to pedogenic carbonate between the north and the south: carbonate was found on gravels almost to the soil surface in the

north and only at depths below 30 cm in the south (Fig. 3).

Initially, we investigated the possibility that the placement of the carbonate on gravel tops at the southern sites was caused by the presence of a past groundwater table within the soil profile. However, (i) the geomorphic setting suggested no such persistent water table, (ii) the soils themselves exhibited no morphological indication of a water table, (iii) the gravelly nature of the soil does not seem conducive to significant capillary movement of water if a periodic water table was present, and, most importantly,(iv) we observed that soils on obvious Pleistocene terraces (reddened Bt horizons, stage II to III carbonate development) elevated several meters above the Holocene deposits also contained carbonate laminations nearly exclusively on gravel tops (Fig. 4b). This not only eliminated the possibility of a ground water explanation, but it suggested that the pedogenic processes observed in the Holocene soils had been operable for considerable periods of time.

The placement of carbonate coatings on gravels appears to be linked to the differences in precipitation seasonality between the northern and southern Baja California peninsula. Although the mean annual precipitation (MAP) and mean annual temperature (MAT) of the four sites are relatively similar (as are all other factors of soil formation), there are sharp differences in the timing of the precipitation (Table 1) and the monthly amounts (Fig. 5a). The carbonate morphology co-varies from north to south in regard to such ecosystem properties as floristic composition and O isotope composition of the pedogenic carbonate (Amundson et al. 1994a).

Back to Top

Differences in Depth to Carbonate

The depth to pedogenic carbonate was 6, 3, 32, and 35 cm at

the 30°, 29°, 28°, and 27°30'N locations, respectively (Fig. 3). The sharp difference between the two most northern and the two most southern sites appears to be based on the intensity of storm events. In general, the two southernmost sites are in the occasional path of summer tropical cyclones from the Pacific (Hastings and Turner 1965), which bring sporadic, but occasionally enormous, amounts of precipitation. Weather records indicate notable differences in intensity of storm events between the northern- and southernmost sites (Fig. 5b): in the north, 50% of the measurable monthly precipitation amounts are 10 mm or less, whereas in the south a larger percentage of measurable monthly precipitation totals are skewed to higher values. Most notably, only the two southern-most sites have recorded monthly rainfalls exceeding 100 mm(approximately 3 to 5% of all months with measurable precipitation).

The approximate amount of water that may be held in the upper 6 cm of soil at 30°N is 6 mm, whereas the amount for the upper 35 cm at 27.5°N is 35 mm (based on field textures and gravel estimates). The depth of leaching in the north reflects closely the typical monthly precipitation amounts (which occur in the cool winter months), whereas the southern site reflects leaching caused by the infrequent, larger events, which are partially attenuated by the high potential evapotranspiration rates during the summer period in which they occur.

Back to Top

Positioning of the Carbonate Coatings

The placement of the carbonate coatings correlates with the depth of carbonate: the shallow Bk horizons in the north have coatings on gravel bottoms, whereas the relatively deep Bks in the south have coatings on gravel tops. The orientation of the carbonate coatings is undoubtedly related to differences in the way environmental conditions drive soil water and solute movement in the contrasting rainfall regimes.

Back to Top

Model of Carbonate Deposition on Gravels

Although pedogenic carbonate formation has been quantitatively studied for decades, only recently have there been attempts to explain the orientation of carbonate on soil gravels (McFadden et al., in review). Clearly, the net initial direction of liquid water movement in well drained desert soils, after a precipitation event, is downward, and this flow is driven by the combined effects of matric, gravitational, and other soil water potentials. Subsequent to this, in most deserts, all this water is returned to the atmosphere via evapotranspiration. The depth of downward water movement before calcite supersaturation reached is a function of climate and soil water holding capacity (Jenny and Leonard 1939; Arkley 1963; McFadden and Tinsley 1985; Marion et al. 1985).

These processes are clear; what is unexplained is how, within zones clearly experiencing net deposition of carbonate (i.e., Bk horizons) for thousands (e.g. this study) to millions of years (Amundson et al. 1996), there can be smaller scale regions where deposition does not occur (i.e. gravel tops or bottoms). This is even more perplexing when we consider that, in many of these soils, the fine-grained fraction surrounding such gravels appears to possess carbonate. We have observed well developed Bk horizons 50 cm or more thick in Mexico (this study), the Mojave Desert (Chadwick et al. 1989), and in Wyoming (Amundson et al. 1994a) where carbonate is almost never found on gravel tops whereas the fine-grained matrix surrounding these gravels is calcareous from pedogenic accumulations. Clearly, within Bk horizons undergoing net additions of dissolved carbonate in downward moving water, there are smaller scale processes both controlling the movement of solutes and/or water and determining the exact location at which carbonate is precipitated on individual gravels.

To help explain our observations, we present a discussion of how soil thermal gradients may contribute, or ultimately control, the locus of carbonate deposition on gravels in desert soil Bk horizons. Although we were forced to consider these processes to explain the unexpected finding of carbonate on gravel tops, the discussion is also consistent with soils in which carbonate is restricted to gravel bottoms and sides.

Soil profiles are seldom isothermal because of seasonal and daily temperature fluctuations with depth. To approximate the seasonal variation in soil temperature at different soil depths in Baja California, we used the mean annual air temperatures (and amplitude of seasonal variations) for our southern-most site (San Ignacio) and soil thermal properties calculated using measured air and soil temperatures for a date palm soil near Indio, CA (NOAA 1978), just to the north of the US/Mexico border (Fig. 1). Using the method described by Jury et al. (1991, p. 188), we calculated the damping depth (287 cm) and thermal diffusivity (709 cm^2 day^{-1}) for this soil. Assuming that annual variation in the air and soil temperature can be described by a sine function, we calculated the variation in soil temperature with depth (Fig. 5c) for the San Ignacio soil, assuming that its thermal properties are similar to the Indio soil. In this exercise, we used the soil temperature model presented by Jury et al. (1991, p. 186). The results of this exercise, although semiquantitative, indicate that in the winter, soil temperature should increase with depth and in the summer, decrease with depth.

At the northern Baja California site, precipitation comes dominantly in the winter months. Although there are certainly large diurnal variations in soil temperature, it is likely that when the winter rains arrive, there is an increase in soil temperatures with increasing depth (Fig. 5c). When summer precipitation arrives for the two southernmost sites, there is likely a strong

decrease in soil temperatures from the surface to greater depths. The maximum average temperature gradients (downward) are approximately 0.018°C/cm in the winter and -0.018°C/cm in the summer(all calculated over the entire profile depth).

We note that the temperature profiles are, of course, only approximate. In addition, at a given depth in any particular soil, there can be differences in temperatures caused by the difference in heat capacities and thermal conductivities of the pore space, the fine earth fraction, and the soil gravels. This spatial variability in soil temperature is also likely important to the placement of pedogenic carbonate in desert soils, as discussed below.

How will the temperature gradients that exist when rainwater enters a soil influence the location of carbonate deposition? We discuss below two mechanisms consistent with our observations that may contribute to this process.

Back to Top

Temperature Effects on Carbonate Solubility

A factor attributable to the thermal gradients is the known decrease in carbonate solubility with increasing temperature (Butler 1982). The solubility product of Ca^{+2} and CO_3^{-2} decreases exponentially with increasing temperature and at 20°C is approximately 50% of its value at 0°C (Butler, 1982). Therefore, in both winter and summer rainfall regimes, the location of carbonate deposition on individual gravels is likely to be on the warmest end of a gravel and in a location relatively low in carbonate solubility.

The actual temperature differences between the top and bottom of a given soil gravel in our Mexican soils is likely to be

small. For a 2-cm-diameter gravel, there will be approximately a 0.036°C difference between gravel tops and bottoms when the thermal gradients are at their most extreme in either winter or summer. Assuming the cool end is at 22°C (for example), the solubility product of carbonate on the warm end will be about 99.89% of that on the cool end. While this is a small difference, it may have an influence on the precipitation of carbonate from the soil solutions. Assuming a uniformly moist gravel at saturation with respect to carbonate at all locations, there will be a small concentration gradient set up from the cool to the warm end of a gravel that will drive solute movement toward the warmer end. The rate of solute diffusion will be dependent on the concentration gradient and the solute diffusion coefficient, which is dependent on water content, etc. (Jury et al. 1991). If this diffusive flux occurs in conjunction with the drying of the gravel, this may account for the observed location of carbonate laminations in the contrasting rainfall zones.

Although this appears to be consistent with the orientation of a given gravel, it does not, at first inspection, explain that the non-gravel matrix immediately next to a carbonate-free gravel surface may indeed be calcareous. This may simply be a function of scale. If it is assumed, in coarse-grained soils such as those we have studied, that during a drying event, each soil particle (gravel, sand, silt) is only poorly connected with its neighboring particle, Ca^{+2} and CO_3^{-2} will diffuse to their own local sink (the warmest point on that particle, or the whole particle if it has no temperature gradient). We did not inspect particles smaller than "gravels" (~ > 2 mm). The smaller particles in these and other soils clearly deserve further attention in carbonate accumulation studies.

Back to Top

Temperature Effects on Water and Solute Movement

Liquid water moves along potential gradients under

isothermal conditions. Under strongly nonisothermal conditions, both vapor and liquid water can move in response to changes in potential caused by thermal gradients (e.g., Gurr et al. 1952; Hanks et al. 1967). In an homogeneous unsaturated soil column placed under a temperature gradient, initially, both vapor and liquid water will move from the warmer to cooler regions. However, Gurr et al. (1952) showed that when a closed, unsaturated soil column was placed under a temperature gradient (1.5°C/cm) in the laboratory, there was eventually sufficient vapor movement that it removed, and reversed, the liquid water potential gradient:"Hence, liquid water will tend to flow in the direction of increasing temperature- a direction which is the reverse of that during the first stage of adjustment." Eventually "a circulating system will therefore operate in which vapor moves in the direction of decreasing temperature and liquid moves in the opposite direction as far as permitted by the presence of conducting water films" (Gurr et al. 1952: p. 343). In the gravelly soils we examined, the conducting water film might be that of an individual gravel.

This experiment was repeated on open, vertically oriented soil columns by Hanks et al. (1967). Analysis of the data also revealed the establishment (after 40 days) of a circulating system: "the net effect of downward flow of water (vapor) due to thermal gradients was counteracted by increased upward flow of water in the liquid phase due to suction gradients" (Hanks et al. (1967) p. 598). In these experiments, the final temperature gradient was approximately -0.33°C/cm.

Field and laboratory studies of stones placed at the soil surface (Mehuys et al. 1975; Jury and Bellantuoni 1976) both show that under heating, stone bottoms remain cooler than the surrounding soil, inducing both heat and water vapor movement to the gravel bottoms (and subsequent condensation of liquid water), a process suggested by the experiments described above.

Buried gravels or stones were not investigated in these studies.

Although thermal gradient will clearly affect water and solute movement, its role in our observations remains uncertain. For thermally induced water movement to form oriented carbonate, each gravel would need to be involved in its own independent circulatory system, with condensation on the cool end and water/solute movement to the warm end where evaporation is occurring. Such a mechanism seems unlikely. Experimental work on gravelly soil columns with carbonate-bearing soil water will ultimately resolve the questions suggested by our field-based observations.

Back to Top

Regional Trends in Carbonate Orientation

To our knowledge, our observation of pedogenic carbonate coatings on the tops of gravels is a novel finding. The major orientation of carbonate laminations in early stages of carbonate development in gravelly soils is generally on gravel bottoms and sides. This is particularly interesting because calcic soils are found in the summer precipitation belts of Arizona, New Mexico, and Texas (as well as much of the Great Plains), but carbonate orientations on gravel tops have not been observed in these areas (O. Chadwick, E. Pendall, C. Monger, and L. Nordt, per. comm.). Although the reasons for this remain unknown to us, there might be (i) some critical temperature regime above which summer rains can produce this orientation, (ii) some critical proportion or amount of summer versus winter precipitation, or (iii) a combination of 1 and 2.

The annual cycles in air temperatures for southwestern U.S. sites receiving summer precipitation, and the southern-most Baja California site, are illustrated in Fig. 6a. The U.S. sites all exhibit a temperature cycle typical of continental stations (cool winters and hot summers). In contrast, the Baja California site (which is

very representative of the other three sites on this transect) shows a strong marine influence: warmer winters and cooler summers than their continental counterparts. In general, the temperature trends do not provide an immediate explanation for why southern and eastern Baja California sites have different carbonate deposition processes than other sites with summer precipitation.

The Baja California sites that have carbonate on gravel tops have similar precipitation patterns, but they differ greatly in total amounts per month, compared with sites in the summer precipitation belt of Arizona and New Mexico (Fig. 6b). New Mexico and Arizona locations receive the bulk of their summer precipitation in July and August, whereas the California and Mexico sites receive much of their precipitation in August and September. More importantly, the Arizona and New Mexico locations receive much larger quantities of total summer precipitation than the Baja California soils. It is possible, if thermal gradients are important to the orientation of carbonate deposition, that relatively large quantities of precipitation cool the soil surfaces and reverse temperature gradients, promoting carbonate deposition on gravel bottoms.

We have tried to determine the extent of the carbonate deposition on gravel tops in the Sonoran desert. Reconnaissance field observations (R. Graham) indicate an absence of carbonate on gravel tops near Twenty Nine Palms, north of Indio. This site is at the southern border of the Mojave Desert winter precipitation maximum. We have not had an opportunity for adequate field observations in other areas that have climatic patterns similar to sites where we have observed carbonates located on gravel tops.

Back to Top

SUMMARY

The effect of precipitation seasonality on soil and vegetation is a factor that has received little recognition when compared with the effect of annual amounts or averages. The Baja California peninsula provides a nearly ideal field setting to observe the effect of precipitation seasonality in the driest region of North America (Hastings and Turner 1965).

The processes responsible for the orientation of carbonate laminations on subsurface soil gravels have not been considered before although attention has been given to oriented carbonates that form on surficial gravels (McFadden et al., in review). However, the top versus bottom orientations of laminations in Baja California appear to be caused by only one environmental difference: seasonality of precipitation. The explanation for the placement of carbonate coatings on gravels in soils of the Baja peninsula, and elsewhere, lies embedded in the physical and biological processes controlling water and solute movement. We suspect that thermal gradients play a decisive role in these processes, but in the absence of time series field measurements of soil heat and water parameters, a definitive explanation remains elusive.

The presence of carbonate laminations on gravel tops in Pleistocene deposits in several widely spaced locations in Baja California suggests the long-term stability of the present soil-forming conditions. The areal and temporal distribution of carbonate coatings on gravel tops - if they are indeed correlated only with summer precipitation - could be an important terrestrial paleoclimate indicator in this area, aiding in a better understanding of long-term circulation and precipitation patterns.

Back to Top

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Back to Top

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